CAMP STANLEY
UNDERGROUND MAGAZINE DESIGN VALIDATION TEST

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INTRODUCTION

Various units of the U.S. Eighth Army's 2nd Infantry Division, located just south of the DMZ in Korea, maintain basic operating loads of ammunition at Ammunition Holding Areas, or "AHA's," located within the boundaries of their camps. In the past, these AHA's have been exempted from the normal Quantity-Distance, or "Q-D," safety hazard ranges established by the DOD Explosives Safety Board (DDESB), because of the transcendent need for the units to have immediate access to their munitions in the event of a combat emergency.

An underground munitions storage facility (Figure 1) has been designed as an alternative to the open storage currently used at Camp Stanley, to provide reduced hazard distances and increased security. The facility will provide 22 parking bays (eight in the first phase of construction which was completed this year, and 14 in the second phase, yet to be constructed). Each bay will accommodate two ammo trucks. Each truck will be uploaded with a unit basic load of artillery ammunition, with a potential maximum of 10,000 pounds Net Explosive Weight (NEW) per truck, or 20,000 lb per bay.

Typical underground munitions storage facilities do not accommodate uploaded vehicle storage. Because the Camp Stanley facility is unique in design, no data exists to indicate that an accidental explosion of the ammo in one bay will not propagate to adjacent bays. Therefore, the DOD Explosives Safety Board requires use of the entire NEW (440,000 lb) capacity of the facility as the Maximum Credible Event (MCE) in hazard range (Q-D) calculations. The Board will, however, allow a reduced MCE when data are shown to support a reduction.

The Camp Stanley Munitions Storage Magazine Validation Test, described in this paper, was designed to evaluate the risk that a detonation of 20,000 lb NEW in one bay would propagate to adjacent bays. If the test results show that a detonation will not propagate, then the explosives safety Q-D can be reduced to that required for the NEW of a single bay. It was determined that a 1/3-scale experiment, simulating an accidental detonation in the Stanley facility, would be large enough to provide meaningful results, yet small enough to be an affordable test.

The basic test program was funded by the U.S. Eighth Army. Additional funds were provided by the KLOTZ Club to acquire additional airblast and ground shock diagnostic measurements. The KLOTZ Club is an international organization of seven countries (France, Germany, Norway, Sweden, Switzerland, the United Kingdom, and the United States) which cooperatively support safety research for underground ammunition storage.

This paper describes the technical data acquired in the 1/3-scale test to validate the Camp Stanley underground magazine design, and presents a comprehensive analysis of (a) the risk of a detonation propagation within the Camp Stanley facility, and (b) the Q-D area recommended for the facility.

OBJECTIVE

The objective of this test program was to evaluate the potential for sympathetic detonation (by prompt communication) of munitions in adjacent storage bays (the acceptors) from an accidental detonation in one bay (the donor) of the Camp Stanley underground magazine.

DESCRIPTION OF TEST

The Camp Stanley Concept Validation Test Program consisted of three high explosive detonations (10.7, 57.9 and 336.0-kg Composition B charges) simulating, at 1/3-scale, accidental explosions of ammunition stored on vehicles in parking bays (or adits) of an underground storage complex in granitic rock. The two smaller charges were for calibration tests, and the large charge simulated the full 20,000-lb NEW of a full-scale storage bay. The 1/3-scale storage bays were constructed to be 6 m long (along centerline), 3.7 m wide and 2.1 m high. The access tunnel was 54 m long, 2.1 m wide, and 2.1 m high. Longitudinal tunnel/adit cross-sections are shown in plan and profile in Figure 2. Internal airblast pressure and thermal (temperature and flux) measurements were made in the access tunnel and acceptor adits. Free-field airblast pressure measurements were made along the extended tunnel centerline outside the portal and on the overburden above the tunnel. Surface ground motions were recorded on the overburden above the tunnel and donor adit.

DONOR AND ACCEPTOR CHARGES

The 336.0-kg donor charge for the main test was packed in a plywood container and placed in the middle (donor) adit on the rear of a M151 jeep (Figure 3). The interior charge container dimensions were 76.2 by 76.2 by 68.9 cm high. The container was positioned on the chamber centerline with the center 1.5 m from the rear wall of the adit. The approximate chamber loading density was 11.1 kg/m^3. Sixty-five inert 40mm projectiles were placed on the fire-wall of the jeep to simulate the debris hazards from unexploded munitions.

To determine the effect of the main detonation on explosive and flammable materials in bays adjacent to the donor bay, representative items were placed in the two acceptor adits on the 1/3-scale test (Figure 4). These materials represented a variety of Hazard Class 1.1, 1.2, and 1.3 materials, including bulk explosives (10 kg of Comp B in two light metal containers), diesel fuel (10 liters in a light metal gas can), boxed 105mm artillery munitions (three boxes of Comp B-filled C445 projectiles with propellant charges), palletized 155 mm projectiles (eight M107 rounds) and propellant charges (eight D541 canisters).

INSTRUMENTATION

The instrumentation program was subdivided into four study areas: internal airblast (tunnel and storage adits), internal thermal effects (temperature and thermal flux), external airblast, and ground motion. The internal airblast and thermal measurements provided essential data for evaluating the risk of sympathetic detonation of materials in the acceptor adits, and provided additional data for further development of airblast prediction theories for accidental detonations in underground magazines. The free-field airblast and ground motion measurements also provide quantitative data to establish hazard ranges.

A total of 25 transducers (13 side-on and 4 stagnation pressure, 5 thermal flux and 3 thermocouples) were installed inside the tunnel and storage adits. Side-on overpressure measurements were made at the entrance to the donor adit (at the juncture with the tunnel wall and in the center of the tunnel), in the center of the acceptor adits, and at nine selected points along the centerline of the access tunnel. Stagnation pressure gage mounts were installed at one point in the rear of the tunnel and at three points between the first acceptor adit and the tunnel portal. The stagnation pressure gages were add-on measurements funded by the KLOTZ Club. Five thermal flux sensors were installed, one in the center of each acceptor adit, one in the rear of the tunnel, and two between the first acceptor adit and the tunnel portal. The locations of the internal instrumentation are shown in Figure 5 (plan view).

A total of 19 gages (7 side-on, and 3 stagnation pressure, and 9 accelerometers) were installed outside the tunnel. Side-on and stagnation pressure measurements were made at ranges of 5, 10, and 25 m from the tunnel entrance to establish flow and dynamic pressure levels along the extended tunnel centerline. Each stagnation gage was mounted on a steel gage mount 75 cm above the ground surface, with a flush-mounted side-on pressure gage immediately below. All other free-field gages were flush-mounted on the ground surface for side-on measurements. The gage distances were measured from the tunnel portal. Free-field airblast gage locations are shown in Figure 6.

DEBRIS COLLECTION

The objectives of the fragment collection portion of the test program was to determine the distribution of metal fragments inside the acceptor adits and in the free-field outside the tunnel portal. Two sources of fragments were of interest; those produced by the breakup of the jeep on which the explosive charge rested, and those from the inert 40mm rounds placed upon the front of the jeep. The collection effort consisted of visually searching the acceptor adits for any metallic fragments and a survey of the area outside the tunnel to record the position (angle and distance) of all pieces recovered.

RESULTS

Peak overpressures measured in the tunnel and acceptor adits are plotted versus distance (from the donor charge initiation point) in Figure 7. A comparison is shown with the airblast pressure predictions computed using the DDESB exit pressure criteria. Although, again, there is considerable data scatter, a least squares fit of the measured pressures in the acceptor adits indicate that the measured pressures were about one-half of the predicted values.

Figure 8 shows a comparison of measured and predicted peak stagnation pressures. The measured peak stagnation pressure was relatively uniform throughout the tunnel. A comparison of the peak internal pressures (side-on and stagnation) from Figures 7 and 8, respectively, is presented in Figure 9. Although there is significant data scatter, these measurements indicate that the pressures flowing to the rear of the facility were approximately half the pressures flowing to the portal.

Peak airblast impulse levels measured in the tunnel are plotted versus distance from the donor charge in Figure 10. A least squares data fit is included for the "to portal" data (i.e., the measurements between charge adit and the portal). It is significant to note, as shown in this plot, that the peak impulse levels in the acceptor adit were comparable to the values obtained in the tunnel, and not a factor of two less as was noted for peak pressures.

A comparison of predicted and measured peak external overpressures along the extended tunnel centerline (0-degree azimuth) is presented in Figure 11. Reasonable agreement is shown between the measured data and the the elvels predicted by the formula given for Inhabited Building Distance in the DOD Ammunition and Explosives Safety Standards (6055.9-STD). A similar comparison between the measured peak free-field pressures (side-on and stagnation) versus range in the vicinity of the tunnel (25-m radius) is plotted in Figure 12. Although there is some scatter, the predicted values for side-on pressure provide a reasonably good estimate for the measured data. However, the predicted stagnation pressure curve falls significantly below the measured data. Stagnation pressure is the sum of the side-on and dynamic pressure, and dynamic pressure is a function of the shock velocity squared. Therefore, higher measured stagnation pressures imply that the spherically expanding blast wave has a higher shock velocity than is predicted by computer moels such as CONWEP (Hyde, 1988). This is an indication that significant jetting of the detonation gases extends outside the tunnel portal.

DEBRIS HAZARDS

The munitions placed in the acceptor adits appeared to have easily survived the detonation of the 336-kg Comp B donor charge. The post-detonation damage to munitions in Acceptor Adit A is shown in Figure 13. The artillery articles were thrown to the rear of the adit with only minor damage resulting. Several of the 155 mm propellant containers sustained buckling damage, similar to that seen in the left center of Figure 13. This damage appears to be associated with shock loading, rather than any form of impact. No debris fragments were found in either acceptor adit. No indication was seen of any debris impact on any of the munitions placed in these adits. The debris hazard within the main tunnel is graphically depicted in Figure 14, which shows a section of the jeep that was blown against, and caught by, one of the stagnation pressure mounts. The containers of diesel fuel placed in the acceptor adits were empty. Since there were no evidence of burning in the acceptor adits, it is assumed that the diesel fuel leaked out following shock loading of the containers and was absorbed in the loose rock of the adit floor.

The locations of metal debris (pieces of 40-mm projectiles and jeep) thrown beyond the tunnel portal were surveyed after the test. In Figure 15, the debris distances from the portal are plotted versus the horizontal angle (measured clockwise from the extended centerline of the access tunnel) to the debris location. The debris distribution was, to some degree, limited by the site topography. A relatively level bench immediately outside tunnel portal extended approximately 30 m over an arc (measured from the extended tunnel axis) from +5° to -90°. This surface was constructed from the spoil material from the underground excavation, and the slopes at the edge of the bench were steep (at or near the angle of repose for broken rock). This accounts for the scarcity of fragments found at negative angles between distances of 30 and 50 m.

Fragments found beyond 70 m were located in a grove of Aspen trees, which retarded further travel.

The external fragment collection area was subdivided into collection zones 10 m long (radially) by 5° of arc (or +/- 2.5°) for analysis purposes. The total fragment density measured for each collection zone was used to calculate the number of fragments per 56 m^2 of area. This density is plotted versus distance from the portal (to the center of each collection area) in Figure 16. Total density is defined as the number of fragments landing in a collection zone, plus all the fragments falling in the sector beyond the specified collection zone, with the total number of fragments divided by the total area of the zone. As seen in Figure 16, the longer-range fragment distances were limited by terrain and trees, as indicated by the down-turn of the distribution curves at 65 m and beyond. However, the fact that the deposition points of the long-range fragments was well below the elevation of the tunnel portal indicates that these fragments would not have traveled significantly farther over level terrain.

AIRBLAST HAZARD ANALYSIS

For the long, "U"-shaped tunnel layout of Camp Stanley, an accidental detonation in a storage adit near a portal will produce a high-pressure shock wave at the nearest portal, and a lower pressure at the farther portal. The time lag between the shock waves exiting the two portals is such that there will be little interaction of the external shock fronts. Actually, the maximum Inhabited Building Distance (IBD) will result from detonations in the storage adits at the rear of either tunnel leg. Shock waves generated by such detonations will arrive at both portals almost simultaneously, resulting in maximum interaction and reinforcement of the external (free-field) shock front outside the portals. A prediction of the far-field pressures under these circumstances is very difficult. The IBD contour shown in Figure 17 was computed by assuming a compounding of the two wave fronts as the limiting upper bound value. Thus, the computed effective exit pressure used to calculated the IBD range was essentially doubled (compared to the exit pressures normally calculated for single-entrance tunnels). As shown in Figure 17, the IBD (to the 8.3-kPa pressure level) was 438 m from the right portal and 435 from the left. The curved egress sections near the tunnel portals are designed to direct the airblast axis away from the inhabited areas of Camp Stanley.

DEBRIS HAZARD ANALYSES

Figure 18 summarizes the predicted external fragment/debris hazard for the Camp Stanley facility. The total fragment density data plotted in Figure 16 is scaled by dividing the distance from the portal (R) by the one-sixth power of the explosives charge loading (Q) in Figure 18. An upper bound line is drawn as a means of estimating the Q-D for debris (one fragment per 56 m^2), assuming a log-log linear decay in fragment density. The estimated Q-D obtained in this manner is 100 $m/kg^{1/6}$. Thus, the estimated Q-D for a 20,000-lb NEW detonation in the Camp Stanley full-scale facility is 456.8 m.

SYMPATHETIC DETONATION ANALYSES

In Figure 19, the peak overpressures measured in the 1/3-Scale Camp Stanley Validation Test tunnel and acceptor adits are plotted versus distance from the charge detonation point. The distances are multiplied by the scale factor to provide an estimate of overpressures in the prototype facility. The estimated threshold for sympathetic detonation by blast pressure and impulse was developed from previous tests conducted by U.S. Army Ballistic Research Laboratory (BRL) (Collis, 1992), in which 155-mm M107 projectiles were placed at different distances from a 227-kg TNT sphere detonation. Since none of the rounds were sympathetically detonated in the BRL test, including those only one metre from the charge, the assumed threshold for this round is defined as the overpressure and impulse values at a range of one metre from a bare 227-kg (500-lb) TNT hemispherical surface charge detonation. The overpressure predicted by CONWEP (Hyde, 1988) for this distance from such an explosive charge is 22.15 MPa. As shown in Figure 19, peak overpressures measured in the acceptor adits on the Validation Test were a factor of two less than overpressures measured in the main tunnel, and an order of magnitude lower than the calculated pressure threshold for sympathetic detonation.

Peak impulse values for the 1/3-scale tunnel and acceptor adits were obtained from integrations of the measured over-pressure time histories. The peak impulse values and corresponding distances from the explosive source were multiplied by the scale factor (3) to convert to prototype values, and are plotted in Figure 20. A comparison between the integrated measured data and the estimated impulse threshold for sympathetic detonation (3189 kPa-msec) is presented in Figure 20 (Note - the impulse threshold was also based on the BRL test described above; i.e, the impulse at 1 m from a 225-kg TNT charge detonation). A least-squares-fit to the entire data set, with (99 percent) confidence limits, is included for comparison in Figure 20. Although the impulse data exhibits considerable scatter, the analysis indicates that the probability of the impulse exceeding the estimated threshold for sympathetic detonation is less than one percent.

SUMMARY OF FINDINGS

The airblast instrumentation used to assess the blast hazard from the 1/3-Scale Camp Stanley Underground Munitions Storage Facility Concept Validation Tests provided extensive and consistent data. Internal total pressures of approximately 2.5 MPa measured along the tunnel axis indicate a strong flow or jetting within the access tunnel. Free-field total- pressure measurements along the extended tunnel axis indicate that flow pressures ranged from 2.3 to 4.5 times the peak overpressure over a distance of 5 to 25 m from the portal.

The formula for Inhabited Building Distance given in the DOD Explosives Safety Standards (6055.9-STD, Rev 4) provides reasonable predictions of external airblast overpressures. The effective exit pressure predicted by the Standards is 1.48 MPa, which is 45 percent greater than the measured pressure of 1.02 MPa. However, the exit pressure calculated by this method provides a reasonable (but conservative) basis for developing the free-field airblast prediction. In addition, the peak airblast pressures measured on the test, along with computed impulse values, are in good agreement with the azimuth decay factor used in this relation.

The terrain in the 1/3-scale test area limited the distances over which free-field (external) airblast instrumentation was placed from the portal. Therefore, the only data available to evaluate the Inhabited Building Distance predicted by the Standards is from a combination of close-in airblast and long-range noise pressure measurements. These data indicate that the Standards yield a realistic, but possibly somewhat conservative estimate of the actual airblast Inhabited Building Distance.

Scaled to prototype values, peak overpressures in the acceptor adits were a factor of two less than overpressures at comparable distances in the access tunnel, and a factor of seven less than the estimated overpressure threshold for sympathetic detonation. The peak impulse values show considerable scatter, but were roughly the same in the access tunnel and the acceptor adits. An impulse data least-squares fit, with confidence limits, indicates that the estimated peak impulse threshold for sympathetic detonation falls outside the 95 percent confidence limit.

No fragments were found in either acceptor adit. Limited ejecta data indicated that the free-field fragment hazard is confined to a 30-degree sector along the extended tunnel centerline. An extension of the upper-bound ejecta line provides an estimated hazardous fragment distance of 458.8 m.

CONCLUSIONS

- The empirical relations given in the DOD Standards (DOD 6055.9-STD, Rev 4) for effective exit pressure and Inhabited Building Distance provide good predictions of external airblast from an internal explosion in the Camp Stanley facility.

- The predicted prototype airblast overpressures are well below the estimated overpressure threshold for sympathetic detonation. Confidence limits for the prototype airblast impulse indicates a probability greater than 99 percent that the critical impulse threshold for sympathetic detonation will not be exceeded for the NEW's planned for the Camp Stanley facility.

- The debris data collected from the 1/3-scale Camp Stanley Validation Test indicates that Q-D for hazardous debris will not be exceeded.

RECOMMENDATIONS

Additional data are needed to evaluate the effect of storage loading density on external hazard distances for ground shock and debris. Existing empirical relations overestimate these hazards for low loading densities. In addition, recent work in Sweden indicates that the distances to which debris was thrown out the access tunnel on the Tunnel/Chamber test could be reduced by a debris trap outside the tunnel portal. Further study is needed to evaluate such methods, and their most effective design, to reduce the external debris hazard.

ACKNOWLEDGEMENT

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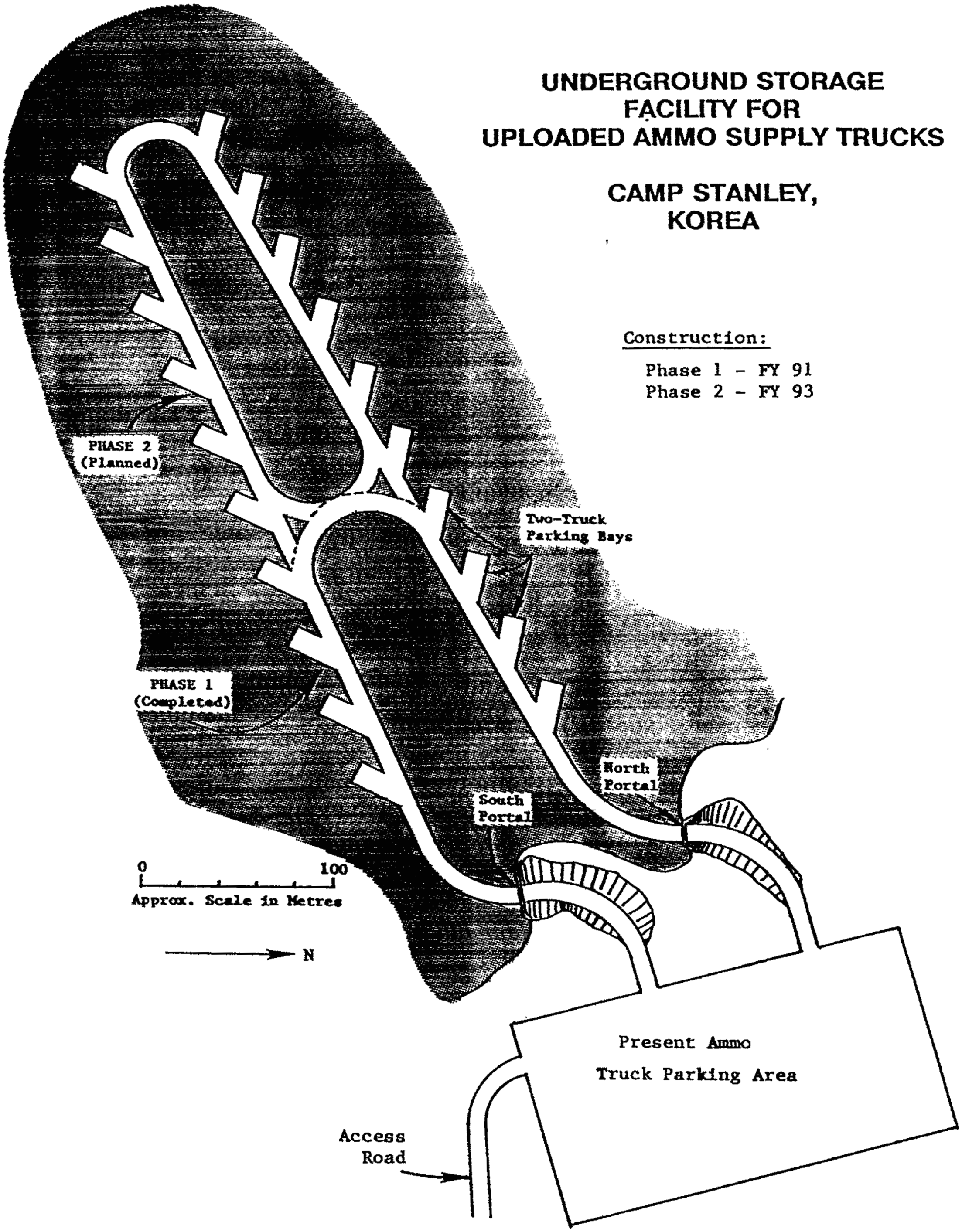

Figure 1. Layout (plan view) for Camp Stanley Underground Ammunition Storage Facility

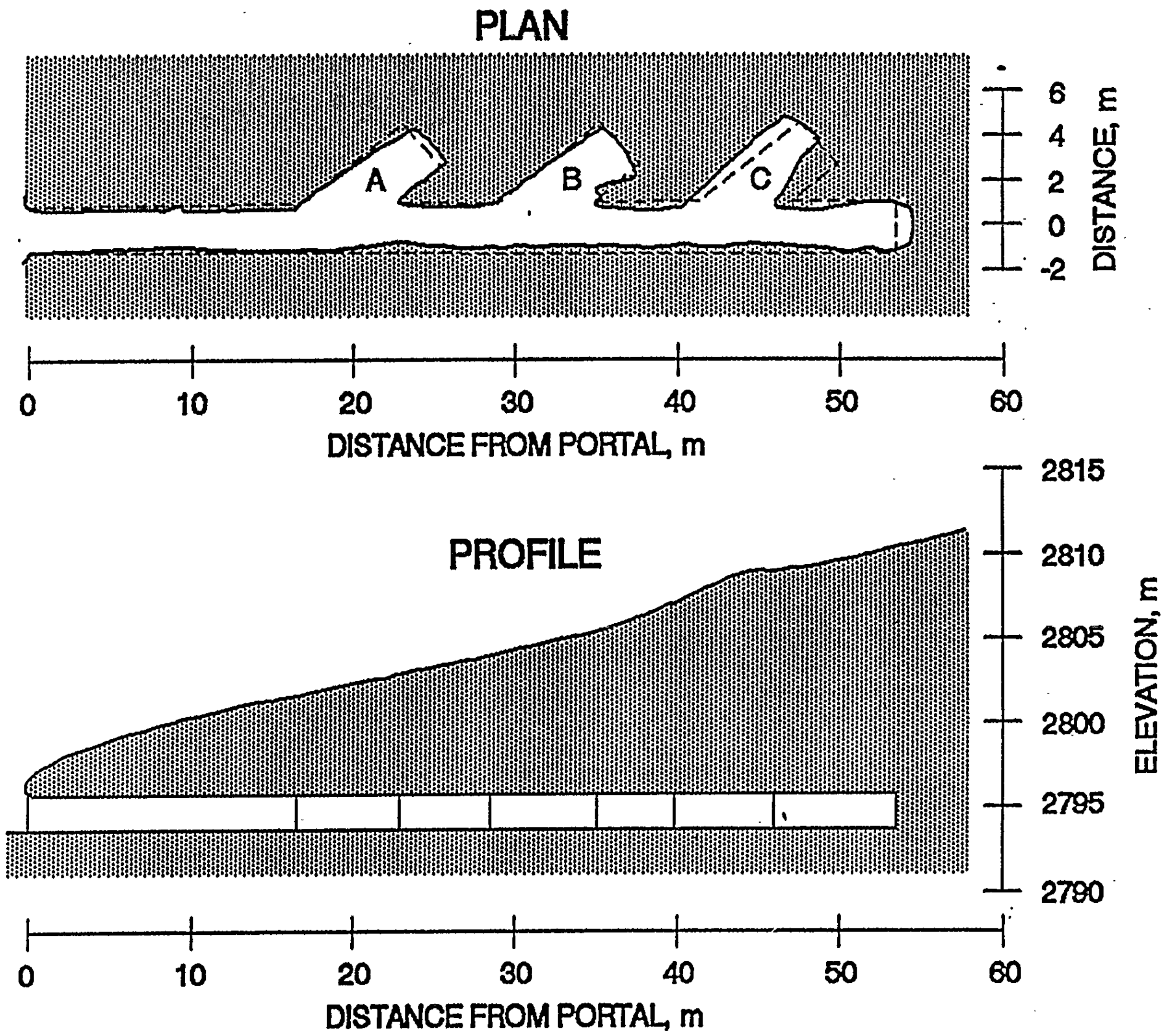

Figure 2. Longitudinal tunnel cross-section (plan and profile) for 1/3-Scale Camp Stanley Validation Test. Letters identify donor (B) and acceptor adits (A and C).

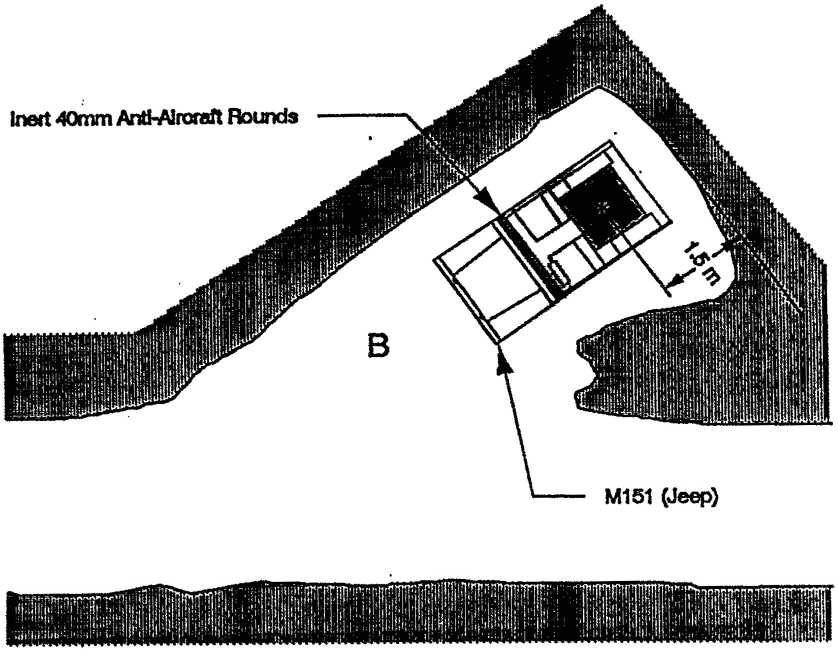

Figure 3. Location of 336-kg Comp B donor charge for Test 3, 1/3-Scale Camp Stanley Validation Test. Explosives were placed upon a surplus M151 vehicle located in adit B.

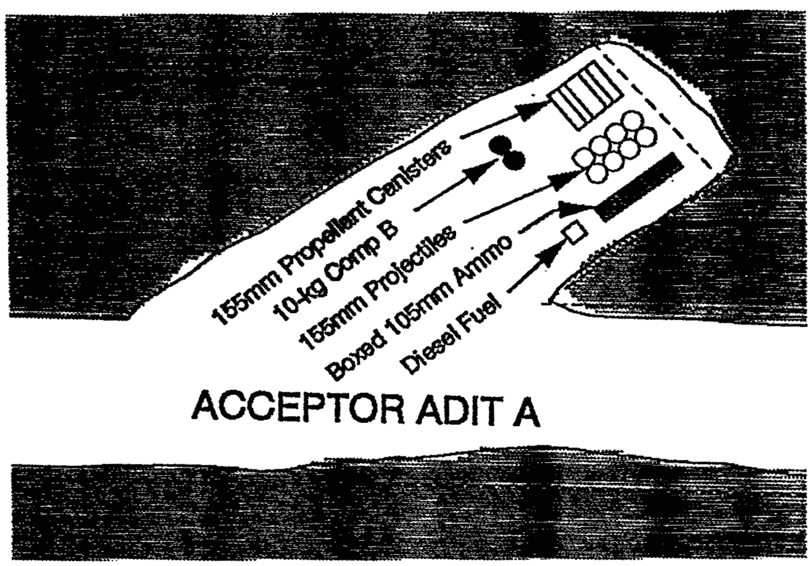

Figure 4. Placement of acceptor munitions within Acceptor Adit A for Test 3.

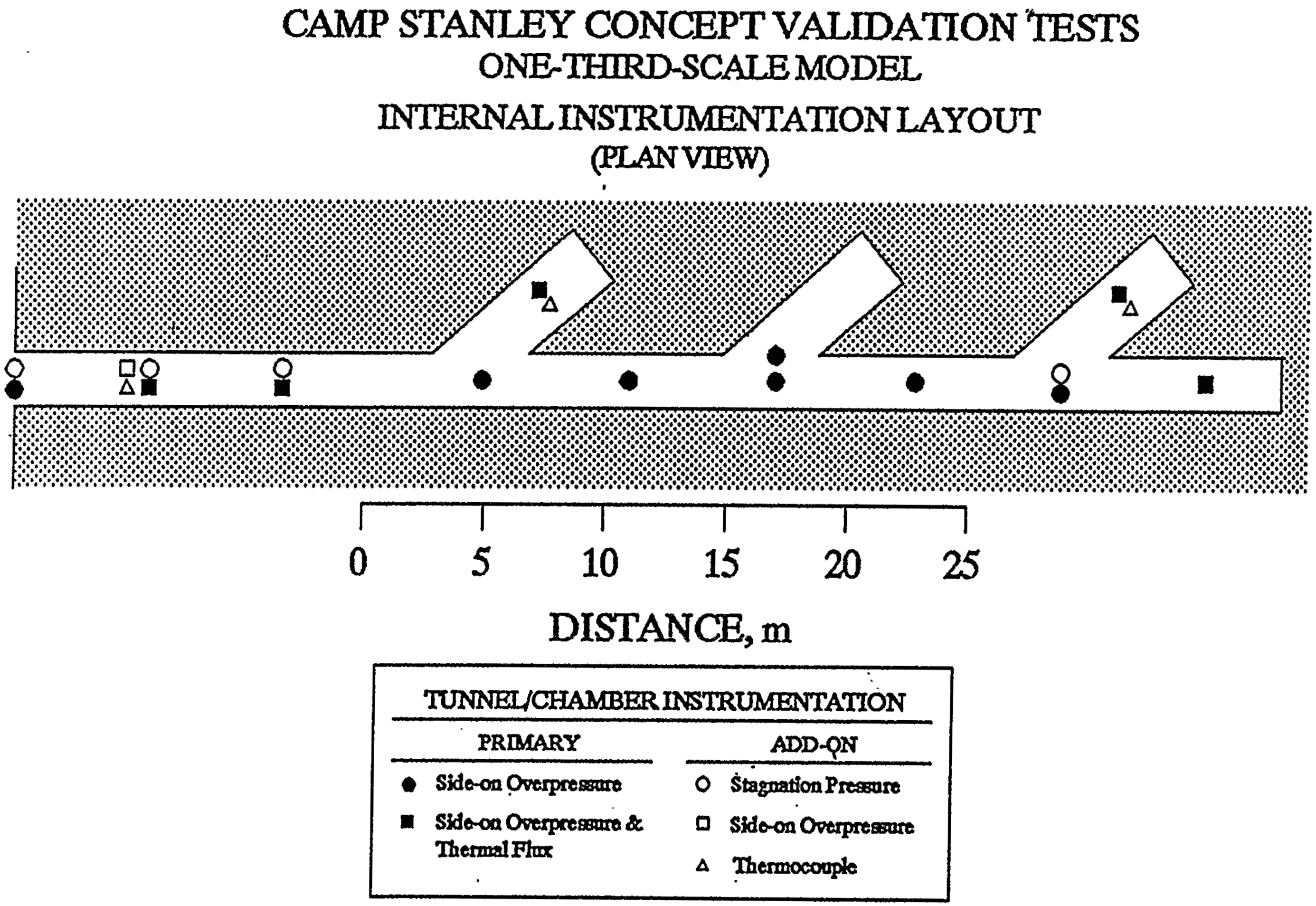

Figure 5. Interior transducer locations for 1/3-Scale Camp Stanley Underground Munitions Storage Concept Validation Test.

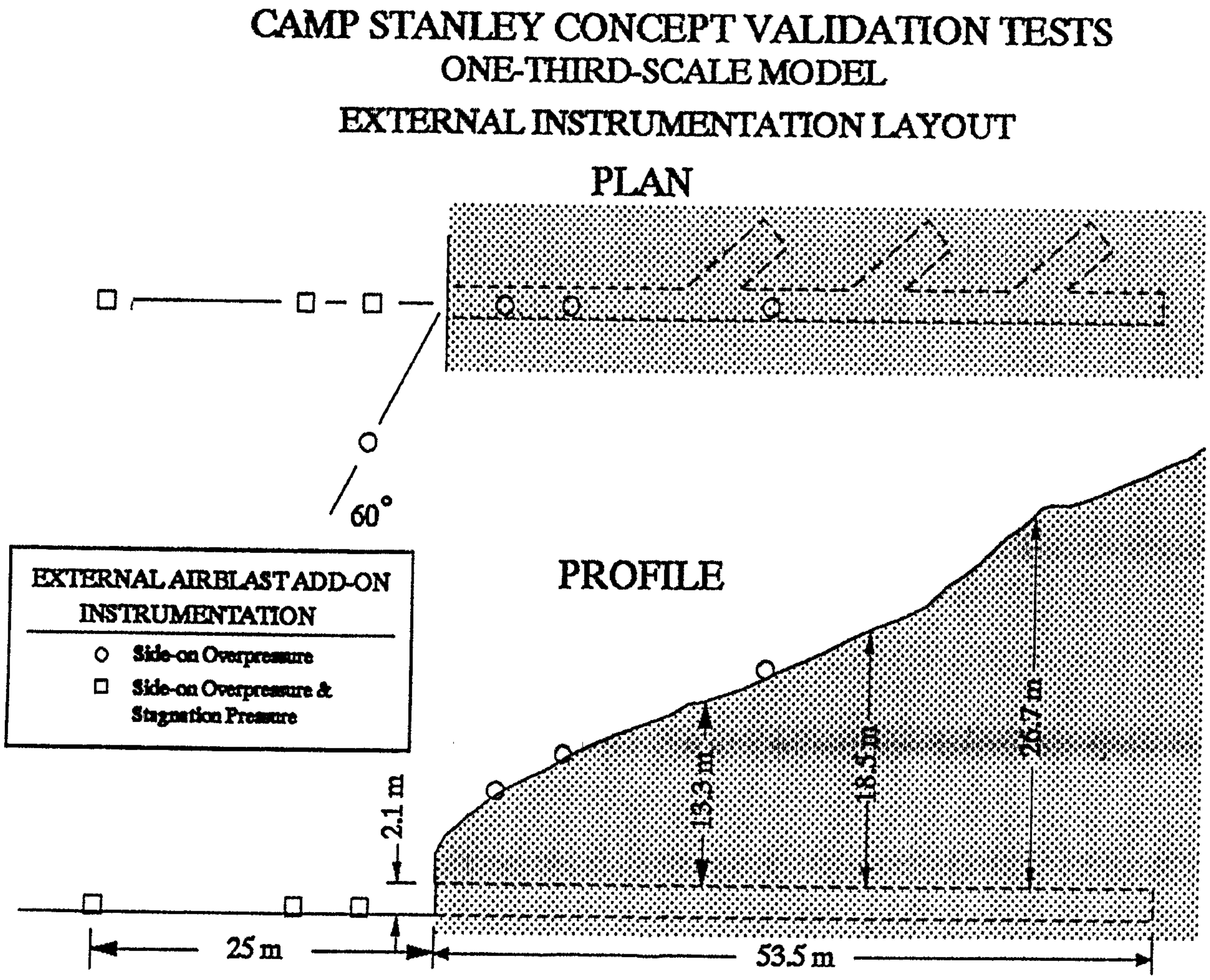

Figure 6. External airblast gage locations, 1/3-Scale Camp Stanley Underground Munitions Storage Concept Validation Test.

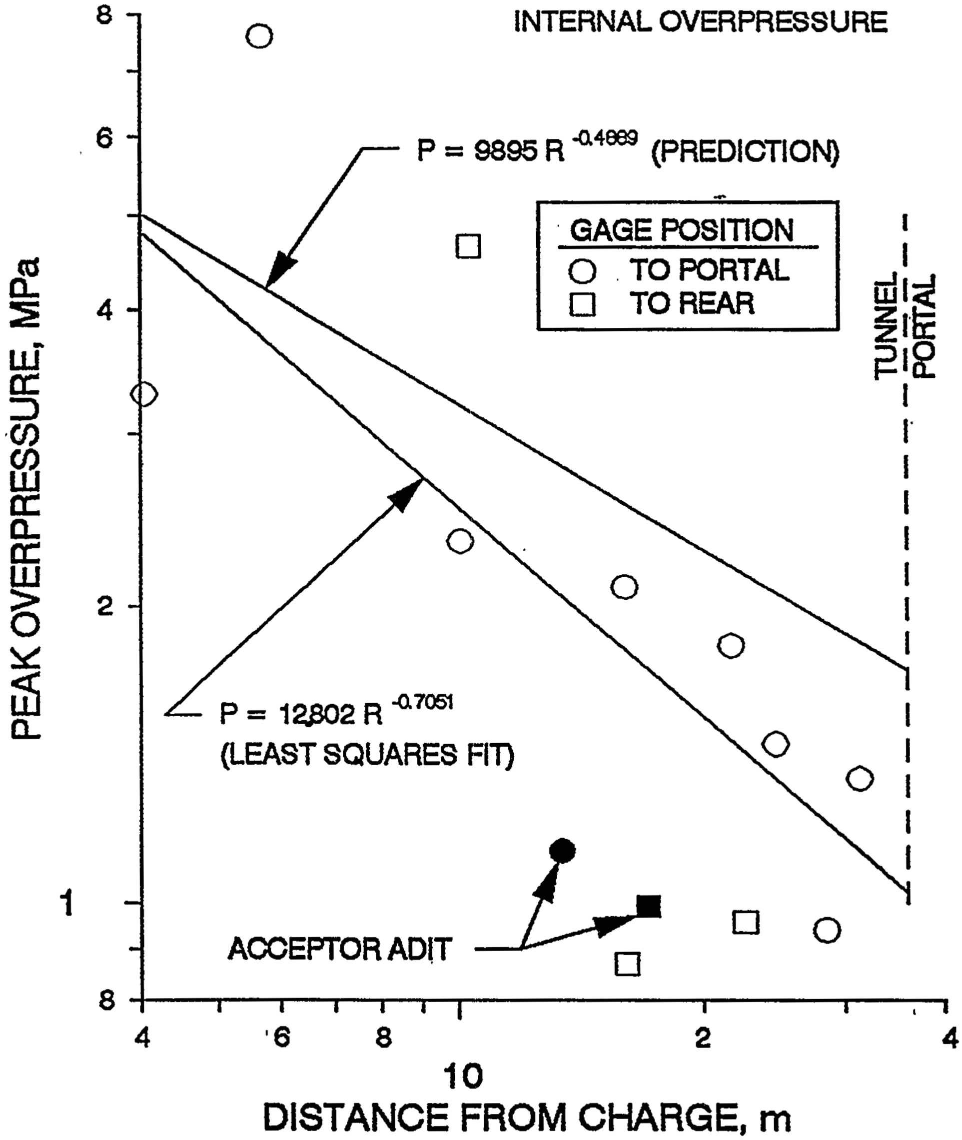

Figure 7. Comparison of peak overpressure measurements, 1/3-Scale Camp Stanley Munitions Storage Concept Validation Test. Gage positions "to rear" are between donor adit and rear of tunnel. Those "to portal" lie between donor adit and portal. Least squares fit includes only "to portal" data.

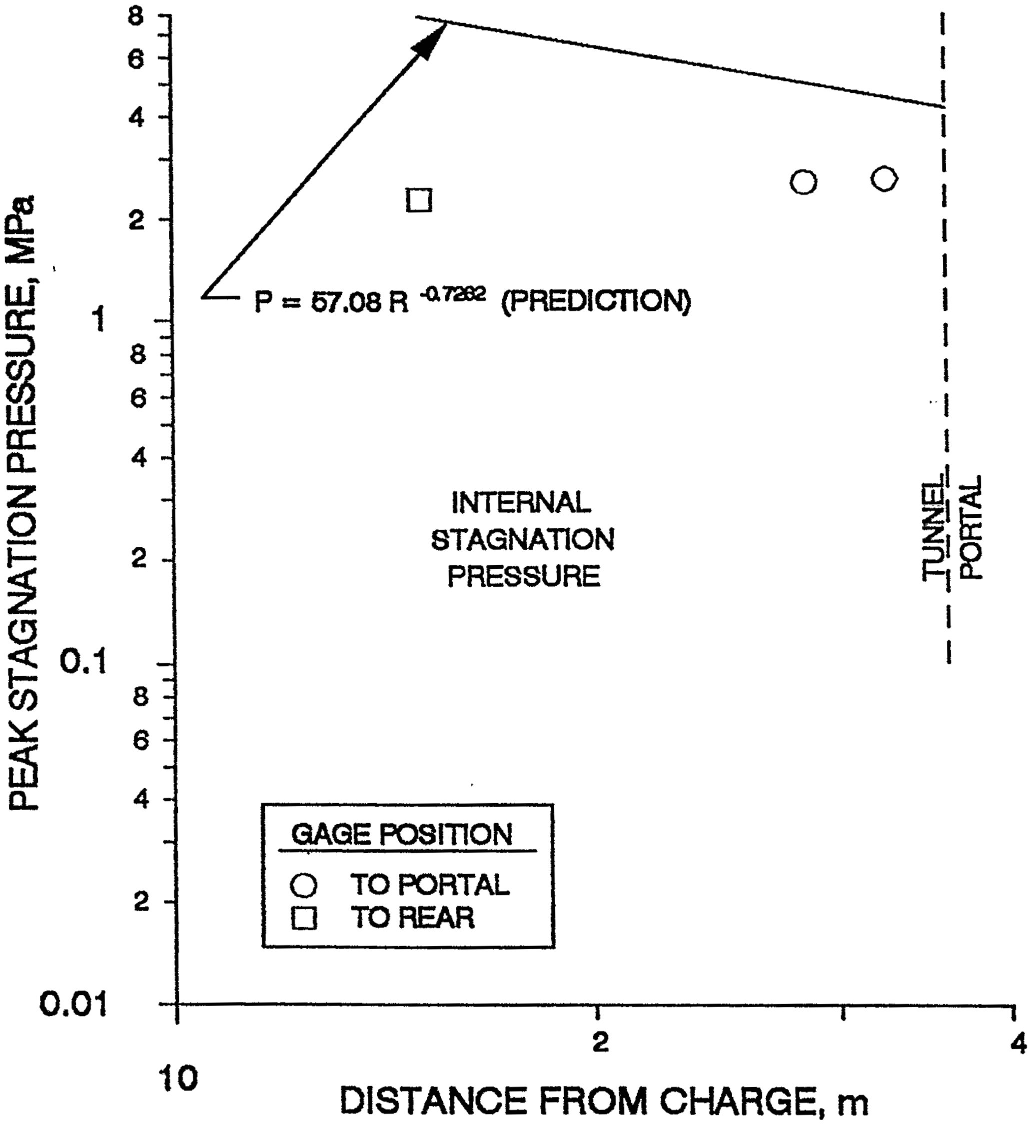

Figure 8. Peak stagnation pressure versus distance from initiation point of donor charge, 1/3-Scale Camp Stanley Munitions Storage Concept Validation Test.

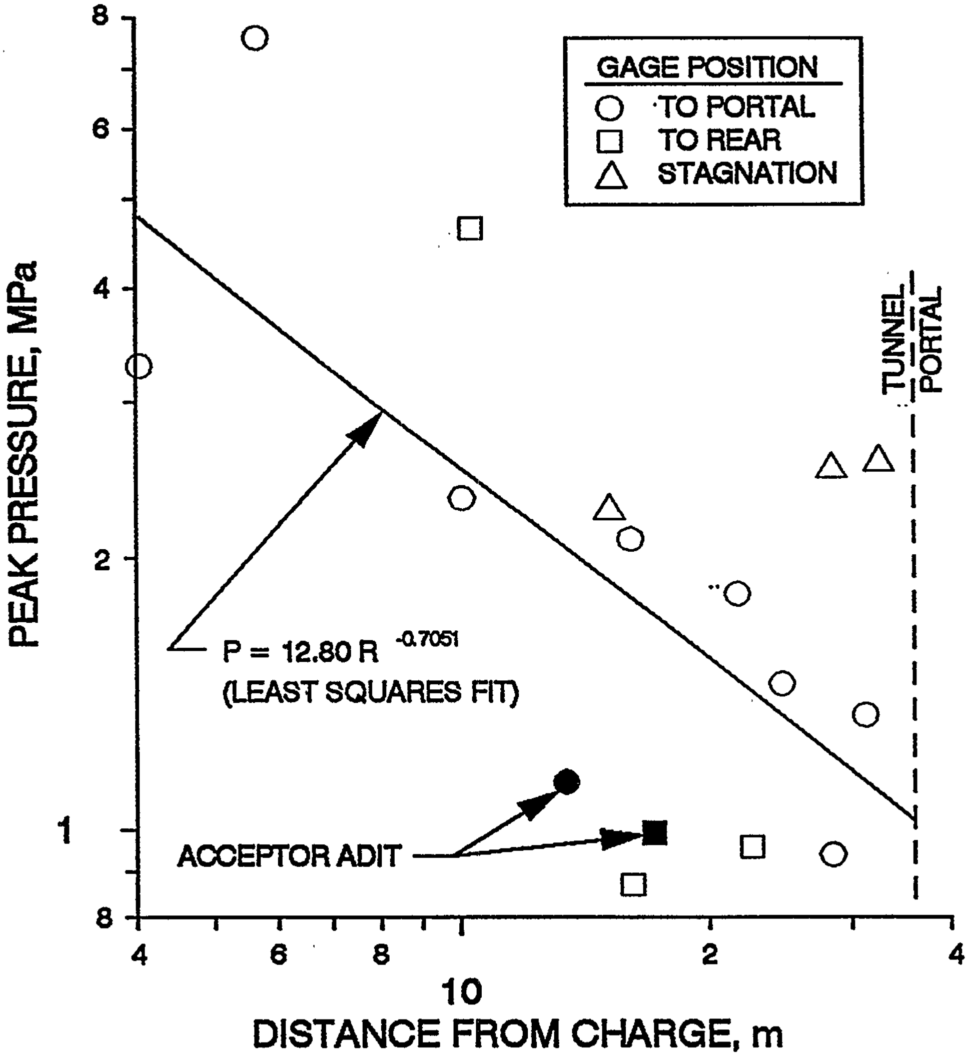

Figure 9. Comparison of internal airblast pressures (side-on and stagnation), 1/3-Scale Camp Stanley Munitions Storage Concept Validation Test. Gage positions "to rear" are between donor and rear of tunnel. The "to portal" positions lie between the donor and the portal. Least squares fit includes only "to portal" data.

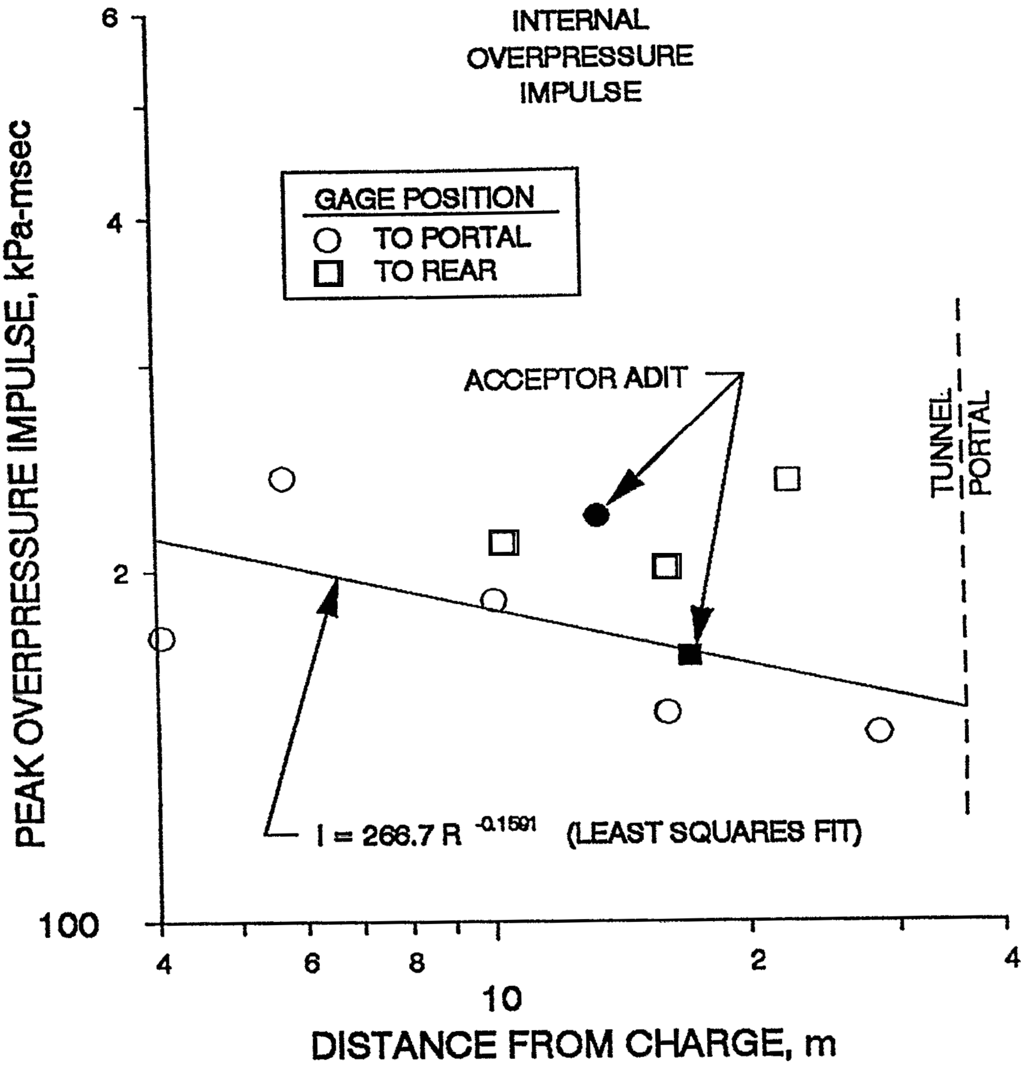

Figure 10. Comparison of peak overpressure impulse, 1/3-Scale Camp Stanley Munitions Storage Concept Validation Test. Gage positions "to rear" are between donor and rear of tunnel. The "to portal" positions lie between the donor and the portal. Least squares fit includes only "to portal" data.

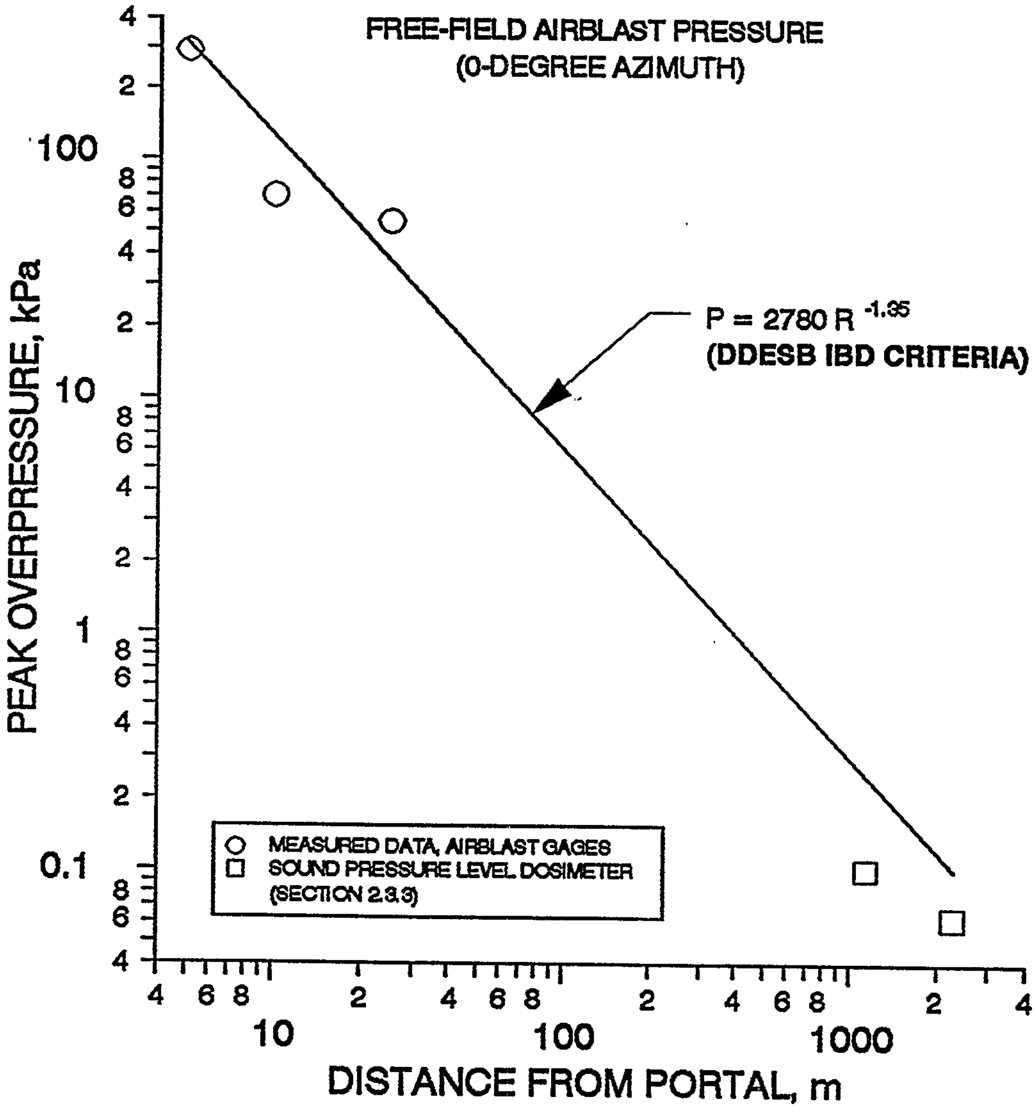

Figure 11. Comparison of predicted and measured free-field airblast data, 0-degree azimuth, 1/3-Scale Camp Stanley Munitions Storage Concept Validation Test.

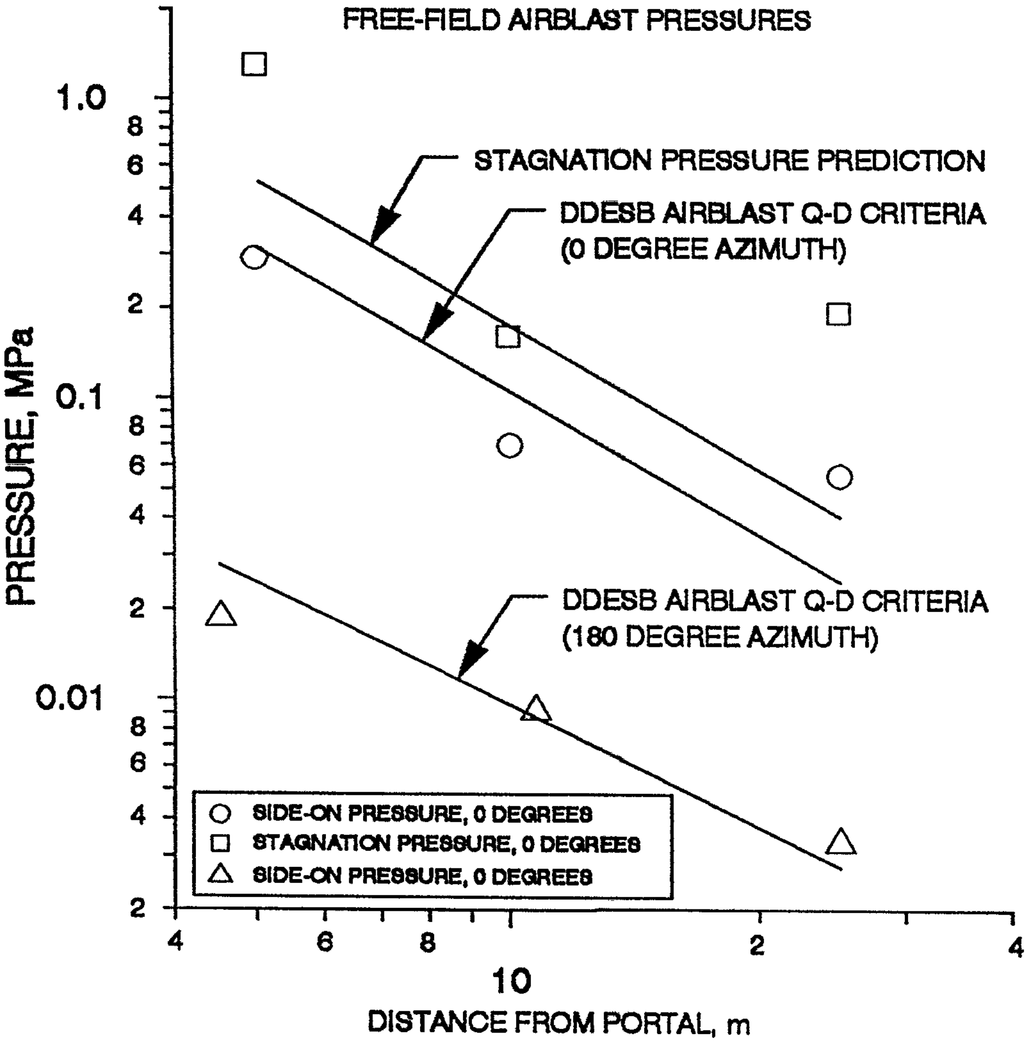

Figure 12. Comparison of predicted and measured free-field airblast pressures (side-on and stagnation), 1/3-Scale Camp Stanley Munitions Storage Concept Validation Test.

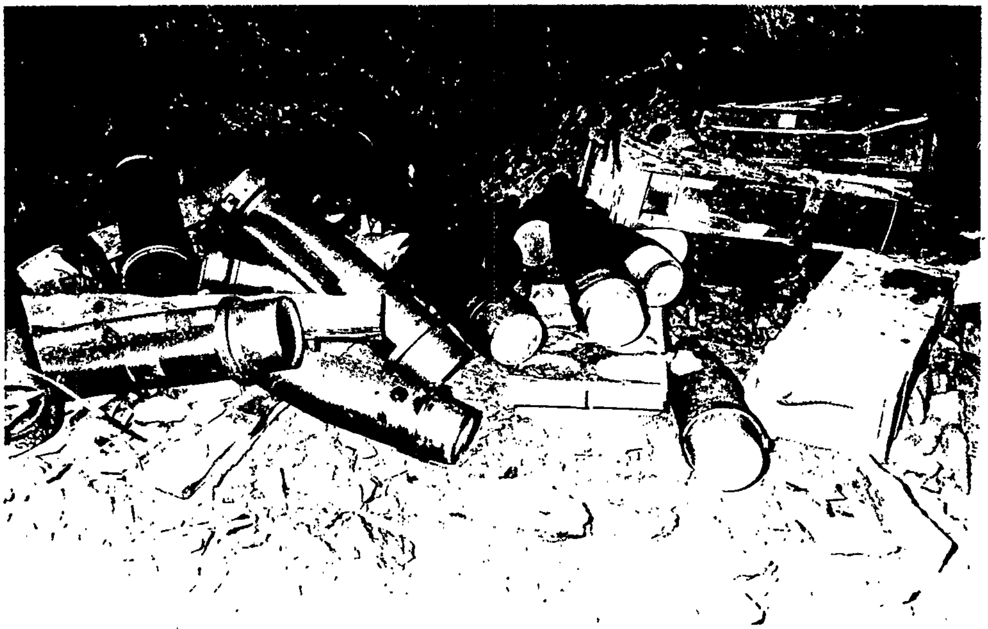

Figure 13. Post test positions of acceptor munitions in Acceptor Adit A.

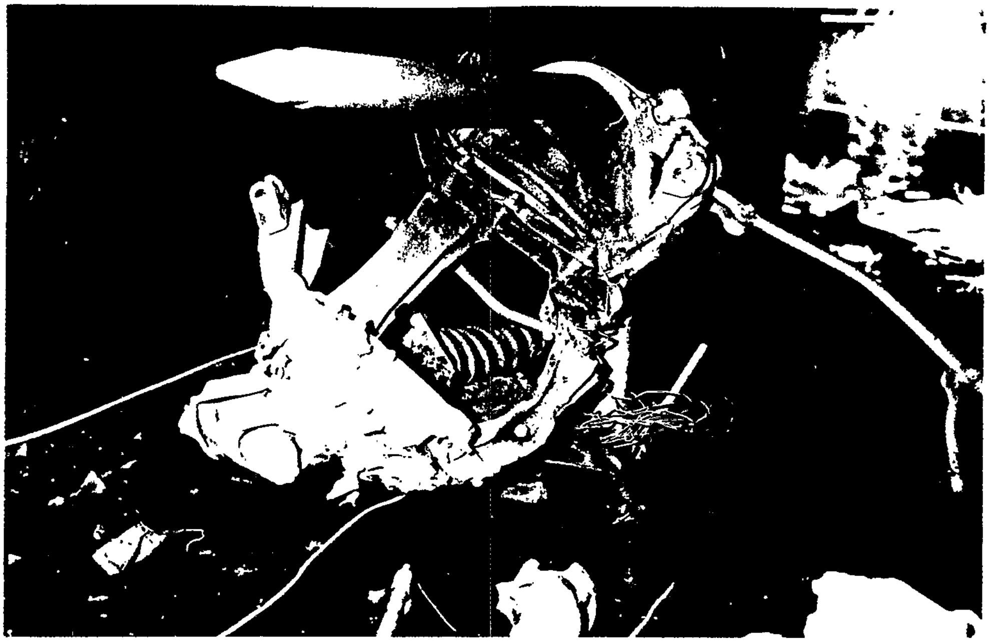

Figure 14. Post test tunnel debris trapped by stagnation pressure mount.

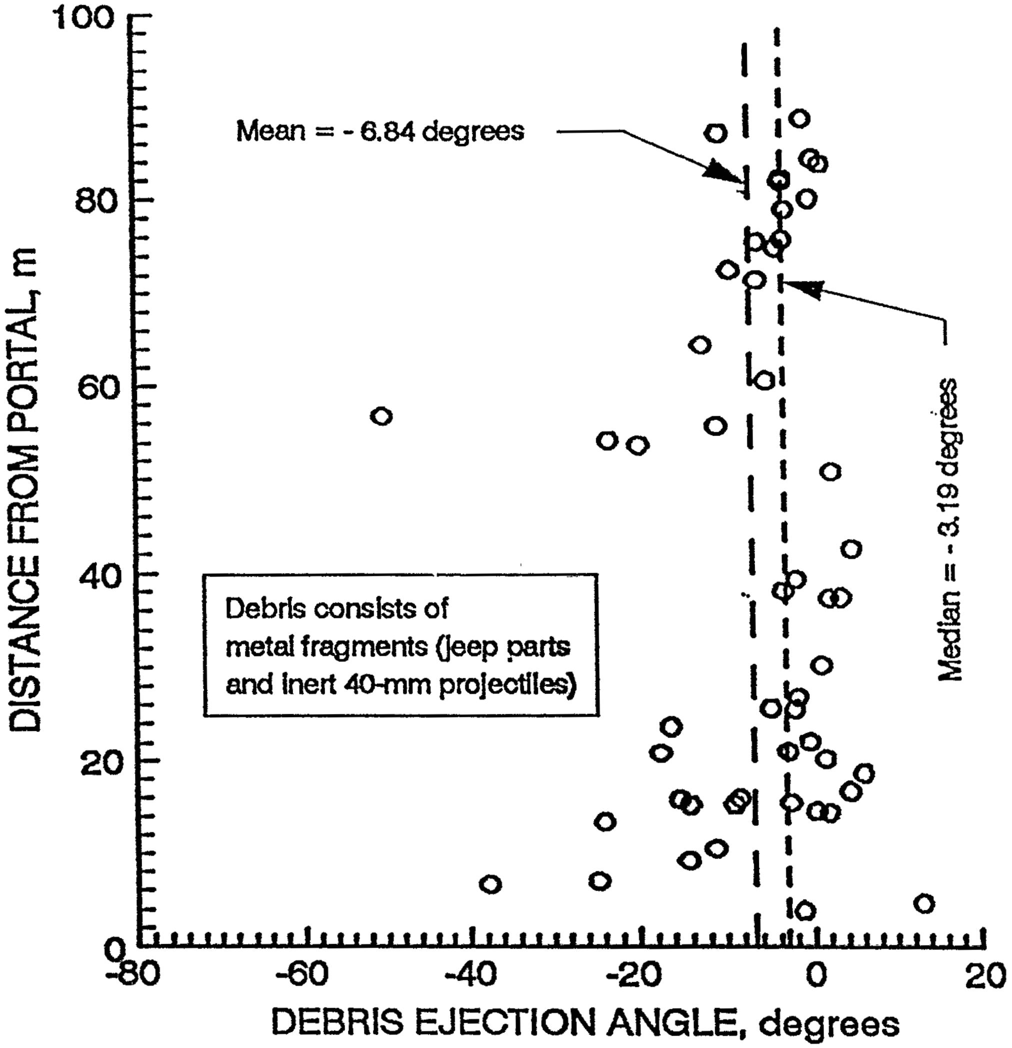

Figure 15. Debris distance from the portal versus angular position (relative to the extended access tunnel centerline).

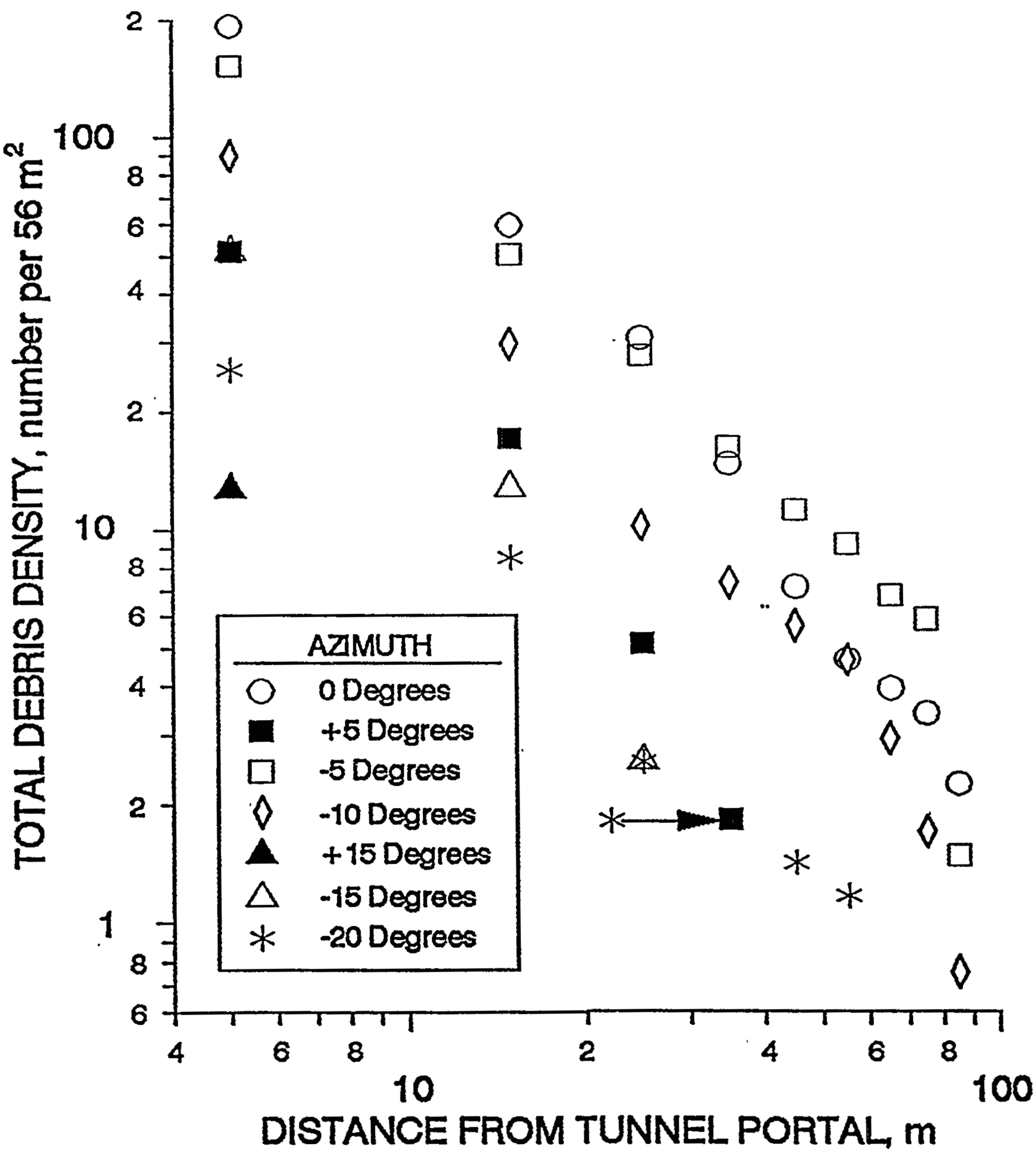

Figure 16. Total debris density versus distance from the portal to the center of the collection zone. Total density is defined as the number of debris fragments found within the collection zone plus the number of pieces which are collected in the same sector beyond the collection zone.

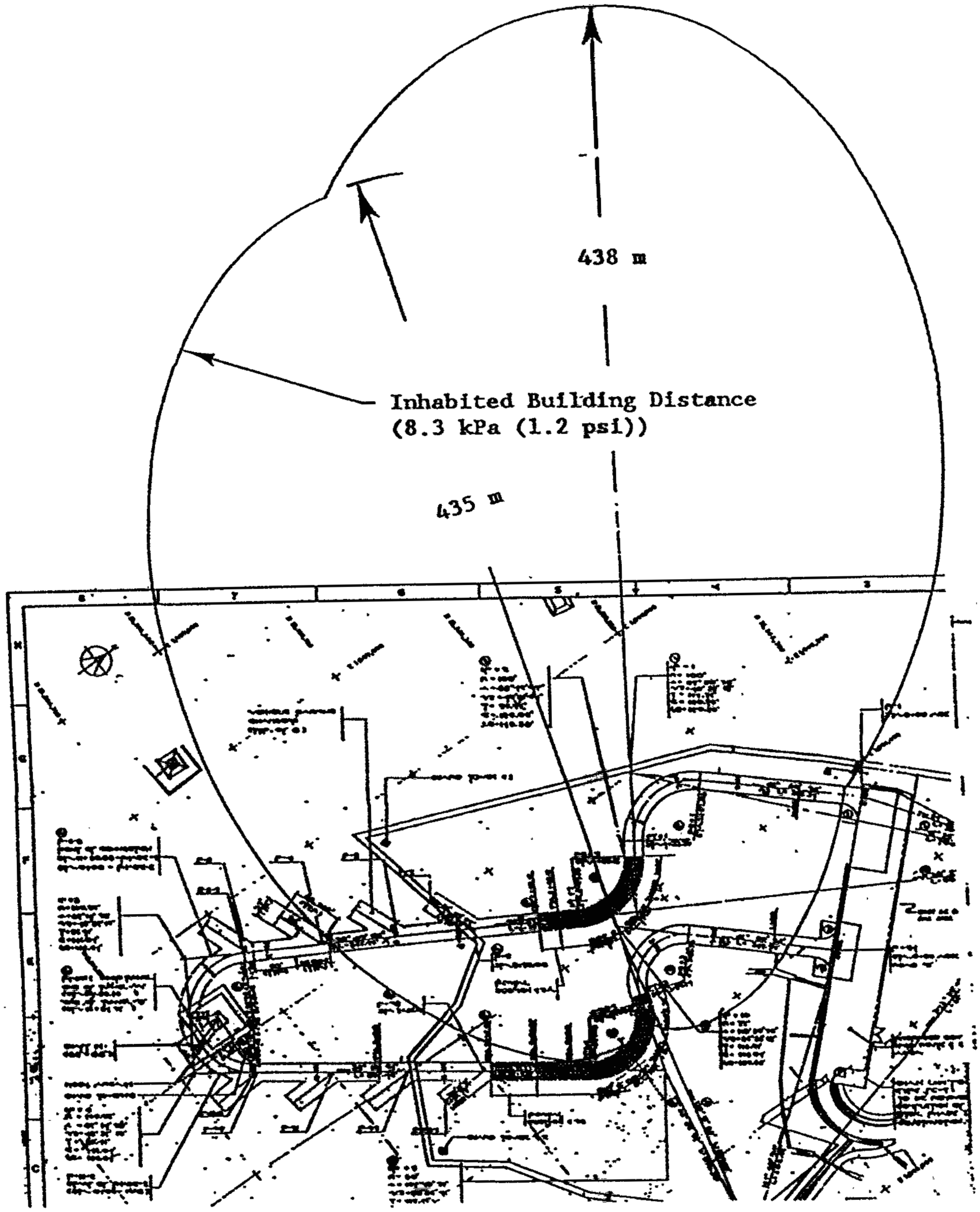

Figure 17. Camp Stanley Underground Munitions Storage Facility airblast Inhabited Building Distances as specified by Standards (DOD 6055.9-STD). Worst case obtained by assuming superposition of airblast shock fronts from accidental detonations of 9080-kg NEQ (20,000-lb NEW) in right and left rear parking adits.

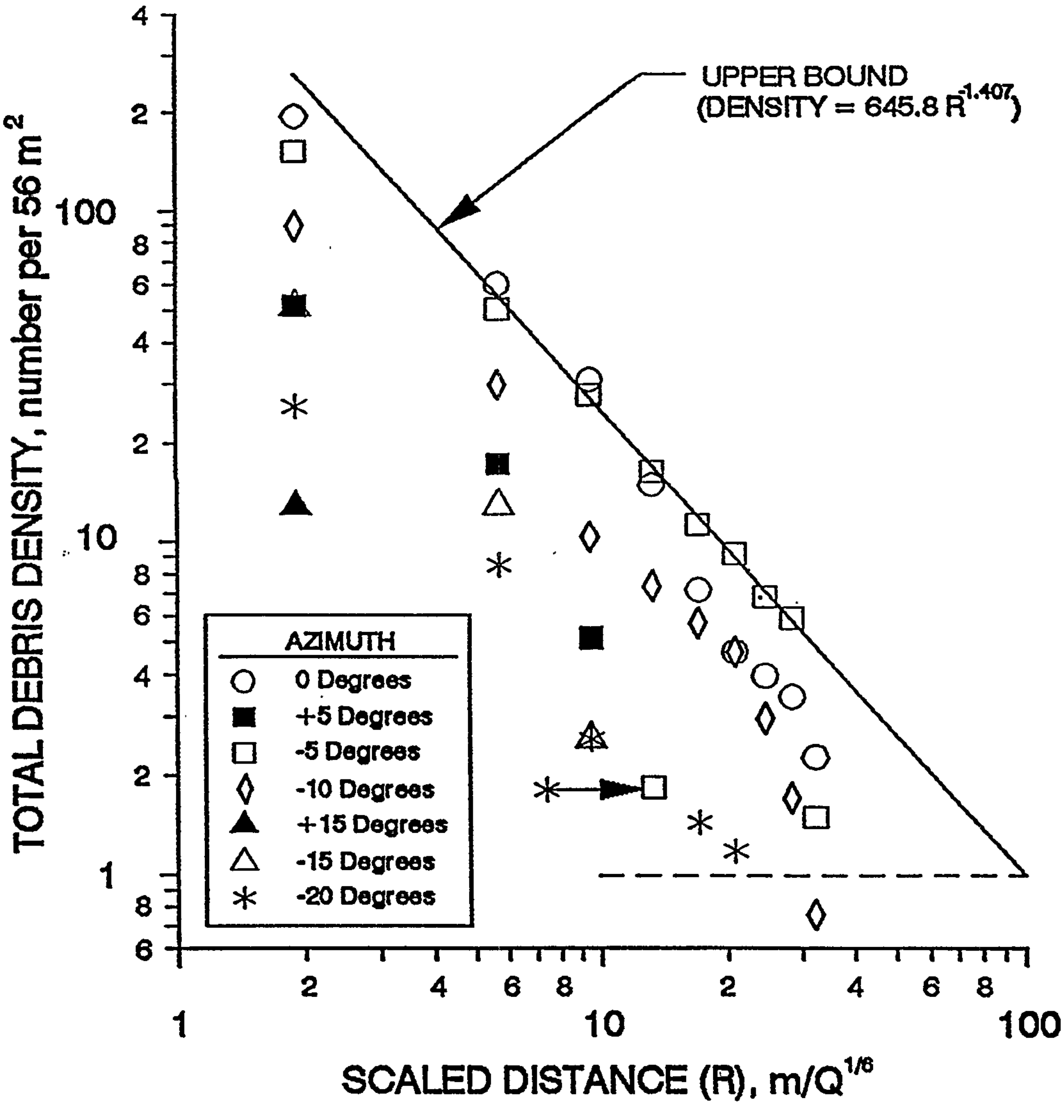

Figure 18. Total external debris density versus scaled distance from the portal, from the 1/3-Scale Camp Stanley Validation Test. Total density is defined as the number of fragments found within the collection zone plus the number of pieces which are collected in the same sector beyond the collection zone.

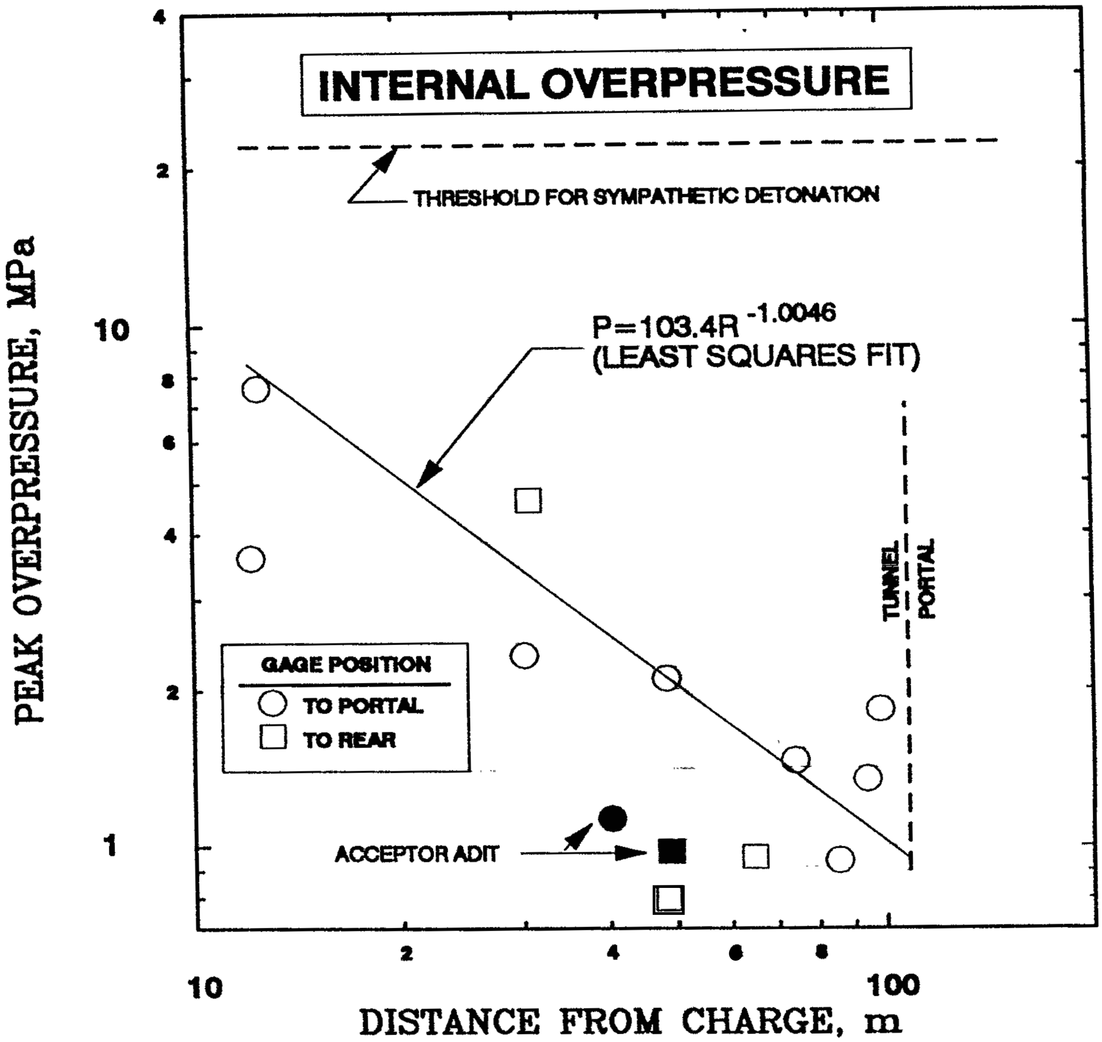

Figure 19. Comparison of peak internal overpressure and threshold for sympathetic detonation defined as the pressure and impulse from a 227-kg (500-lb) surface detonation at a range of 1 metres. CONWEP calculated values of overpressure and impulse are 22.15 MPa and 3189 kPa-msec, respectively.

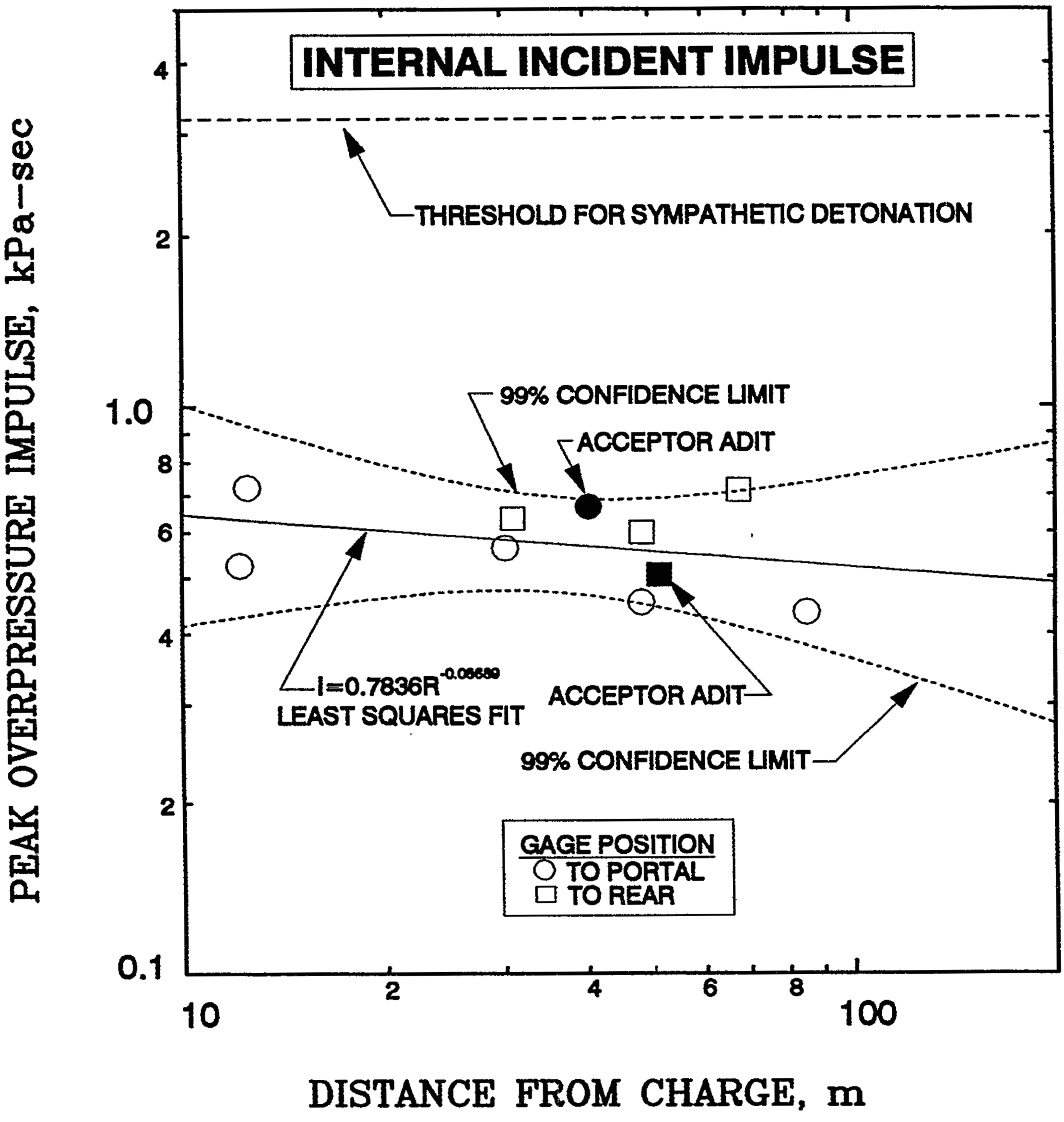

Figure 20. Comparison of peak internal incident impulse and threshold for sympathetic detonation defined as the pressure and impulse from a 227-kg (500-lb) surface detonation at a range of 1 metres. CONWEP calculated values of overpressure and impulse are 22.15 MPa and 3189 kPa-msec, respectively.